

SATELLITE SNOWCOVER AND RUNOFF MONITORING IN CENTRAL ARIZONA

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ABSTRACT

The operation of multipurpose reservoirs in semiarid central Arizona requires timely and dependable snow-melt information. Conventional ground surveys and aerial observations have been used in an attempt to monitor the rapidly changing moisture conditions in the Salt-Verde watershed. Since 1974, timely satellite imagery has provided repetitive snowcover observations to assist the managers of the Salt River Project in the operation of their reservoir system.

Results of studies in central Arizona indicate that multispectral Landsat imagery permits rapid and accurate mapping of snowcover distributions in small- to medium-sized watersheds. Low-resolution (1 kilometer or 0.6 mile) meteorological satellite imagery provides the synoptic daily observations necessary to monitor the large and rapid changes in snowcover. Satellite and microwave telemetry systems are used to furnish near-real time data from streamflow gages and snow-monitoring sites.

Seasonal runoff predictions by conventional index models and a modified hydrometeorological model (HM) were compared. Significant reductions in the standard error for seasonal runoff predictions (March-May) were obtained using the HM model. Short-term runoff predictions using snowcover depletion models were also tested. Statistically significant correlations between short-term snowcover depletion rates and runoff rates were determined for selected periods.

INTRODUCTION

Snowfall provides an important renewable source of water for irrigation, hydroelectric-power generation, and municipal and industrial uses in the Western United States. In semiarid central Arizona the efficient operation of multipurpose reservoirs for both water conservation and the reduction in peak floodflows

requires timely and dependable information on the rapidly changing rates of snowmelt and runoff (Kirdar et al., 1977).

The area of the Salt-Verde watershed is about 34,000 km² (13,000 mi²) and ranges from about 400 to 3,900 m (1,325 to 12,670 ft) above mean sea level (Fig. 1). The annual

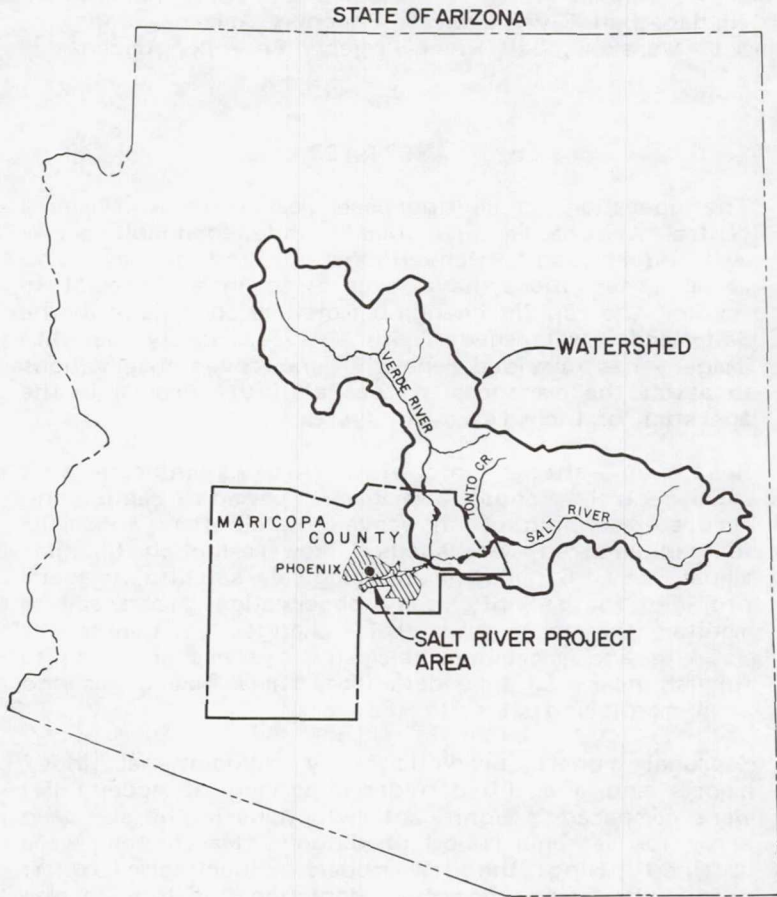


Fig. 1—Salt-Verde watershed

precipitation ranges from less than 250 mm (10 in.) to more than 640 mm (25 in.). (See Green and Sellers, 1964.) About half the annual precipitation comes from winter storms that produce about 75 percent of the mean annual runoff (Kirdar et al., 1977). The extremely variable runoff of the Salt and Verde Rivers is stored in six reservoirs near Phoenix; the reservoirs have a combined storage capacity of about 2,500 hm³ (2 million acre-ft). The reservoirs provide water for municipal, industrial, and

irrigation use in the 101,000-hm² (250,000-acre) Salt River Project area, which includes most of metropolitan Phoenix (Fig. 1). In addition, the reservoirs also furnish hydroelectric power and limited flood protection to the Phoenix area.

Runoff from the Salt-Verde watershed is characterized by frequent and extreme variations. For example, the second smallest annual runoff volumes since 1913 occurred in 1977, and the second largest runoff volumes occurred in 1978. These extremes have produced significant economic impacts. For example, the floods in March 1978 in Maricopa County resulted in the loss of four lives and more than \$33 million in property damage (U.S. Army Corps of Engineers, 1979).

Historically, snowcover conditions in the Salt-Verde watershed were evaluated by ground surveys and more recently by repetitive aerial reconnaissance flights. Near-real time information on streamflow rates is provided by a network of observers that report by telephone to the Salt River Project in Phoenix. Since 1974, the U.S. Geological Survey and the Salt River Project in cooperation with the National Aeronautics and Space Administration (NASA) have evaluated repetitive aerial and satellite snowcover observations and tested the satellite data collection systems for telemetry of hydrometeorological data in central Arizona.

The Salt-Verde watershed is one of four major test sites included in the NASA-sponsored Applications Systems Verification and Transfer (ASVT) Project. The purpose of the project is to develop applications of satellite observations for snowcover mapping and to predict snowmelt-derived streamflow volumes (Schumann, 1975). The purpose of this paper is to summarize the results of the evaluations and to describe the techniques developed for snowcover mapping and for making runoff predictions.

AERIAL SNOWCOVER OBSERVATIONS

Since 1965, light aircraft have been used to make low-level reconnaissance flights over the Salt-Verde watershed to map snowcover distributions and to estimate snow depths and runoff conditions (Warskow et al., 1975). The quality of the snowpack information thus obtained is a direct function of the experience of the observer and the conditions of the flight.

Techniques for using low-cost 35-mm oblique photographs of aerial snow markers from 300 m (980 ft) above the terrain were developed and tested to obtain snow-depth information. The photographs provide a permanent record of snow depths that can be evaluated in the office as opposed to making hazardous low-level—less than 50 m or 160 ft—visual observations of the aerial snow markers (Schumann, 1975).

The availability of frequent satellite snowcover observations has greatly reduced the necessity for routine aerial reconnaissance flights over the Salt-Verde watershed. Significant savings have resulted, and the time that flight crews must be exposed to hazardous low-level flights over mountainous terrain has been greatly reduced. However, aerial observations will continue to provide valuable information on snowcover distributions and snow depths during periods of cloud cover that preclude effective satellite snowcover observations.

SATELLITE SNOWCOVER OBSERVATIONS

Snow could be detected in eastern Canada in some of the images taken by the first weather satellite—TIROS-I—as early as April 1960 (Schneider et al., 1976). In March 1969 photographic imagery taken by the Apollo 9 astronauts indicated the general feasibility of using satellite snowcover observations to provide the synoptic coverage needed for mapping snowcover distributions over the Salt-Verde watershed; however, aerial observations showed that frequent repetitive coverage was required to monitor rapid changes in snowcover.

Landsat System

The experimental Landsat satellite system consists of satellites placed in nearly circular, sun-synchronous, polar orbits at altitudes of about 925 km (575 mi). Multispectral scanners (MSS) aboard the satellites provide high-resolution imagery (80-m or 260-ft ground resolution) that covers 185- by 185-km (115- by 115-mi) areas of the surface of the Earth in the visible and near-infrared parts (from 0.5 to 1.1 μm) of the spectrum (National Aeronautics and Space Administration, 1976). Two Landsat satellites can provide coverage of any ground point every 9 days. The Landsat imaging system is shown diagrammatically in Figure 2. The Landsat MSS imagery can be considered virtually orthographic when used for direct mapping at a scale of 1:1,000,000—the scale that is commonly used for snowcover mapping in Arizona (Fig. 3).

Visual interpretation of 1:1,000,000 Landsat MSS band 5 (0.6 to 0.7 μm) imagery allows rapid and direct mapping of snowcover distributions using conventional photointerpretation techniques. The snowline is traced onto a transparent overlay that contains the watershed outline and major drainages, and the areal extent of the snowcover is determined using a manual planimeter or a suitable grid. Although this technique allows inexpensive measurement of snowcover distributions, the degree of precision is dependent on the skill and experience of the interpreter.

Color-additive viewing of multispectral Landsat imagery enhances the contrast between snowcovered areas and bare rock

and greatly facilitates snowcover mapping in densely forested areas. Snowcover measurements can be made from color-composite images using the transparent overlay technique described by Schumann (1978).

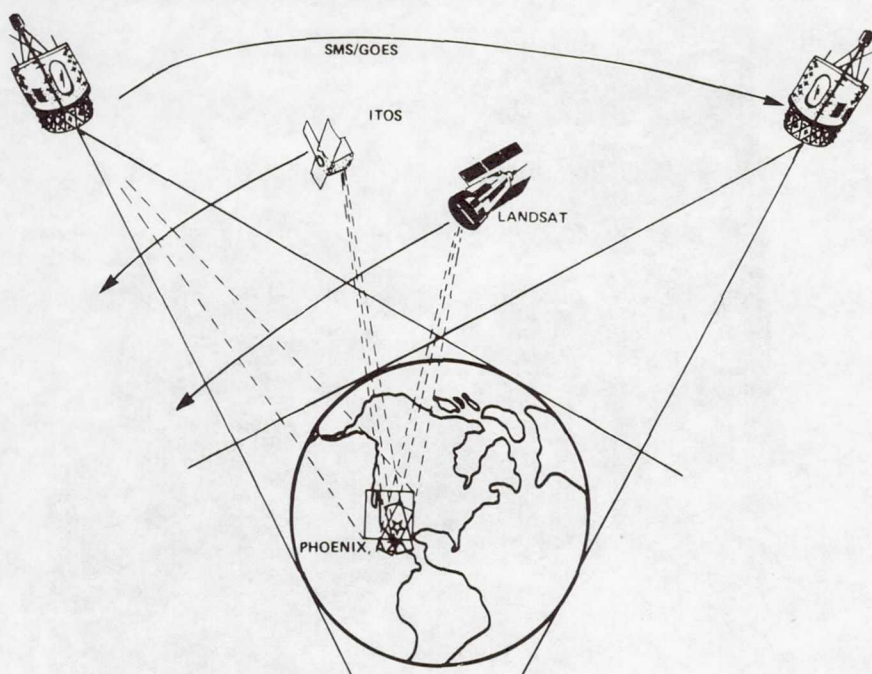


Fig. 2—Satellite imaging systems

The use of electronic density-slicing equipment and appropriate watershed masks allows the rapid determination of the percentage of snowcovered area over small to intermediate watersheds. The density slicer makes a television scan of a masked transparency copy of the black and white satellite image, the enhanced image is displayed on a color television monitor, and the percentage of snowcovered area is measured by means of the electronic planimeter (Schumann, 1978).

The Landsat MSS imagery is available in digital form on computer-compatible tapes (CCTs). Several systems have been developed to produce snow maps from computer-processed digital imagery (Salomonson and Rango, 1975). The systems can provide snow maps of high precision at slow to moderate speed.

The main limitation of using Landsat imagery for snowcover mapping in central Arizona is that only one observation is available every 9 days for a part of the Salt-Verde watershed. Six Landsat images taken on 3 consecutive days are required to

cover the entire watershed (Fig. 3). Winter cloud cover over the mountains often prevents effective Landsat snowcover observations for long periods of time.

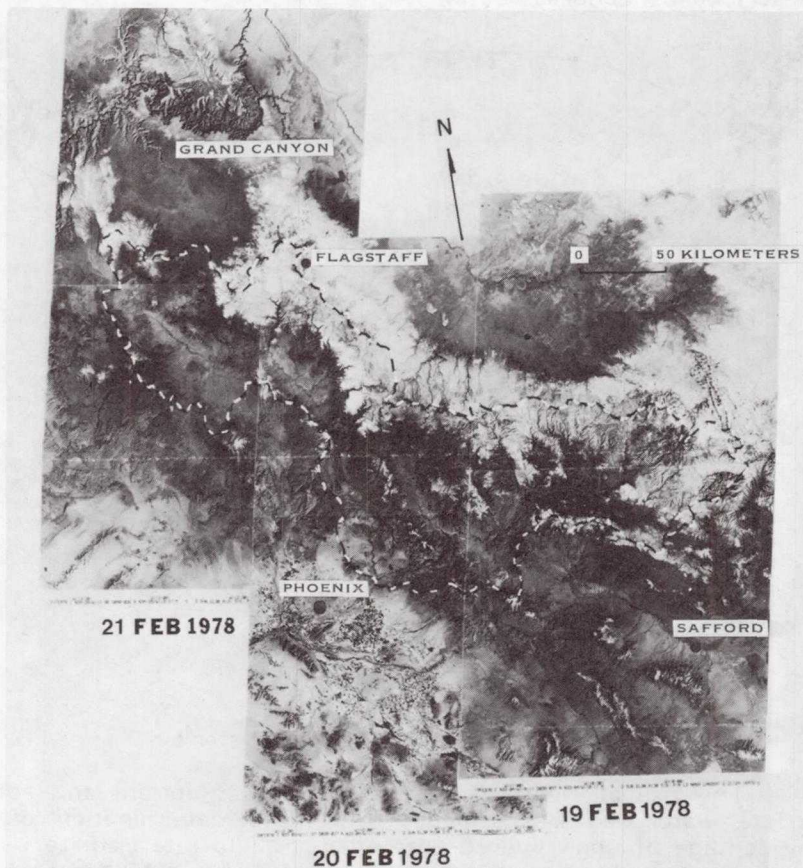


Fig. 3—Landsat image mosaic of the Salt-Verde watershed

The use of photographic copies of Landsat imagery and simple overlays permits direct mapping of snowcover distributions at a low cost. Although the multispectral character of Landsat imagery permits the use of a variety of image-enhancement techniques that facilitate snowcover mapping in densely forested areas, these techniques require expensive specialized equipment. Computer processing of digital Landsat imagery is slow and expensive compared with other methods of image processing.

Improved TIROS Operational Satellite System (ITOS)

The National Environmental Satellite Service (NESS) has used the Improved TIROS Operational Satellite (ITOS) series of

improved Television Infrared Observational Satellite (TIROS) operational satellites (NOAA series) to produce satellite-derived areal snowcover maps of selected river basins including the Salt-Verde watershed (Schneider et al., 1976). The satellites operate in sun-synchronous polar orbits about 1,500 km (930 mi) above the Earth. Very high resolution radiometers (VHRRs) aboard the satellites provide daily coverage of the Western United States in the visible spectrum (0.6 to 0.7 μm) and twice-daily coverage in the thermal infrared (10.5 to 12.5 μm) part of the spectrum (McGinnis, 1975). The imaging system is shown diagrammatically in Figure 2.

The VHRR imagery provides horizon-to-horizon coverage, has a spatial resolution of about 1 km (0.6 mi) at the subpoint, and has a nominal scale of about 1:10,000,000 (Fig. 4). The

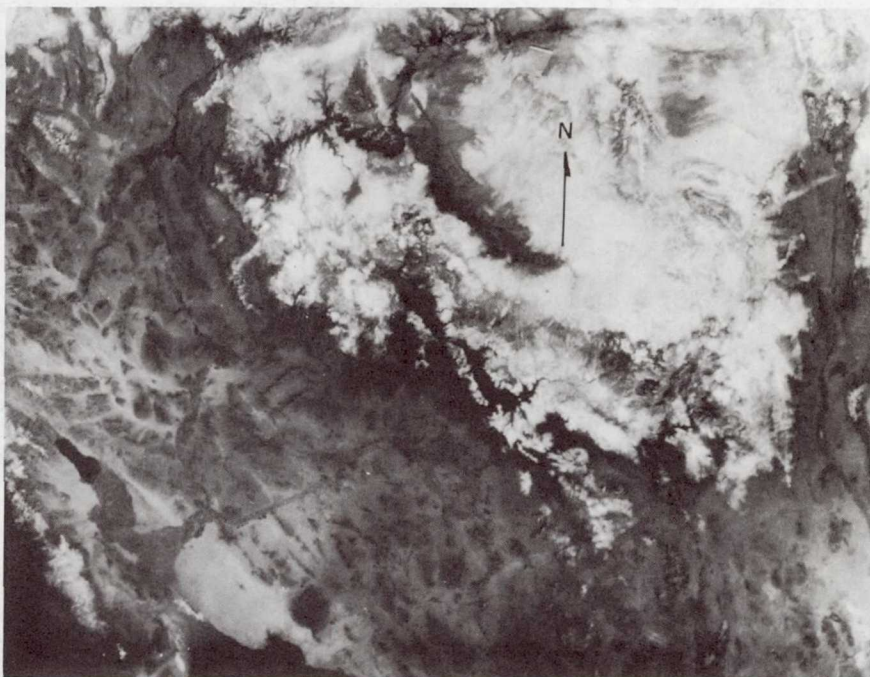


Fig. 4—Enlarged NOAA VHRR image taken in the visible part of the spectrum, March 15, 1978

imagery provides a highly distorted panoramic view of the surface of the Earth that requires geometric correction before it can be related to planimetric basin maps. Specialized optical equipment is used to enlarge and stretch the VHRR imagery and to project the corrected image onto small-scale basin maps. The snowline as visually interpreted on the corrected image is then

traced onto an overlay of the basin map, and the percentage of snowcovered area is then determined either by manual or electronic-planimeter methods.

SMS/GOES Satellite System

The synchronous meteorological satellites (SMS) now in geostationary orbit are prototypes for an operational satellite series designated "Geostationary Operational Environmental Satellites (GOES)." The satellites are in geostationary orbits at about 35,000 km (22,000 mi) above the Earth—their position with respect to the Earth remains fixed. The subpoint of the eastern satellite is at longitude 75° W. over the equator; the subpoint of the western satellite is at longitude 135° W. (Breaker and McMillan, 1975).

The SMS/GOES satellites acquire Earth imagery in the visible (0.55 to 0.75 μm) and thermal infrared (10.5 to 12.6 μm) parts of the spectrum by means of spin scan radiometers (VISSRs). Although the VISSR sensors can image almost the entire Earth (full disk) per scanning cycle, sectors of limited and specified geographical areas are extracted for detailed study (Fig. 5). The sectorized SMS/GOES visible imagery has a maximum spatial resolution of 1 km (0.6 mi) at nadir and is routinely available every 30 minutes (Breaker and McMillan, 1975). The SMS/GOES imaging system is shown diagrammatically in Figure 2.

The VISSR imagery produces a distorted view of the surface of the Earth that changes in scale and resolution north and south of the equator; however, the distortion tends to be fairly constant. Specialized optical equipment can be used to correct the VISSR imagery and to project it onto planimetric basin maps. The position of the snowline can then be plotted, and snowcover measurements can be obtained either by manual or electronic-planimeter methods.

Advantages and Limitations of Meteorological Satellite Imagery

The main advantage of using imagery acquired by the NOAA and SMS/GOES satellites for snowcover mapping in central Arizona is that the systems provide daily observations of the entire Salt-Verde watershed. Daily synoptic observations are required to monitor the large changes in snowcovered area that occur during periods of rapid snowmelt. A comparison of imagery taken simultaneously in the visible and infrared parts of the spectrum can sometimes be helpful in differentiating between clouds and snowcover.

The main disadvantages of using imagery taken by the NOAA and SMS/GOES meteorological satellites for snowcover mapping are the low resolution and geometric distortion of the imagery. The geometric distortions in the VHRR imagery are

highly variable, but the distortions in the VISSR imagery tend to be more constant. Research now being conducted by NESS indicates that the necessary geometric corrections, image enhancements, and snowcover measurements may be accomplished by computer processing of the VISSR digital data (R. S. Gird, National Environmental Satellite Service, written commun., 1978). A review of current SMS/GOES imagery for Arizona prior to aerial snow-reconnaissance flights has provided valuable information that improved not only the efficiency of the missions but the safety of the flights relative to the effects of incoming storms.

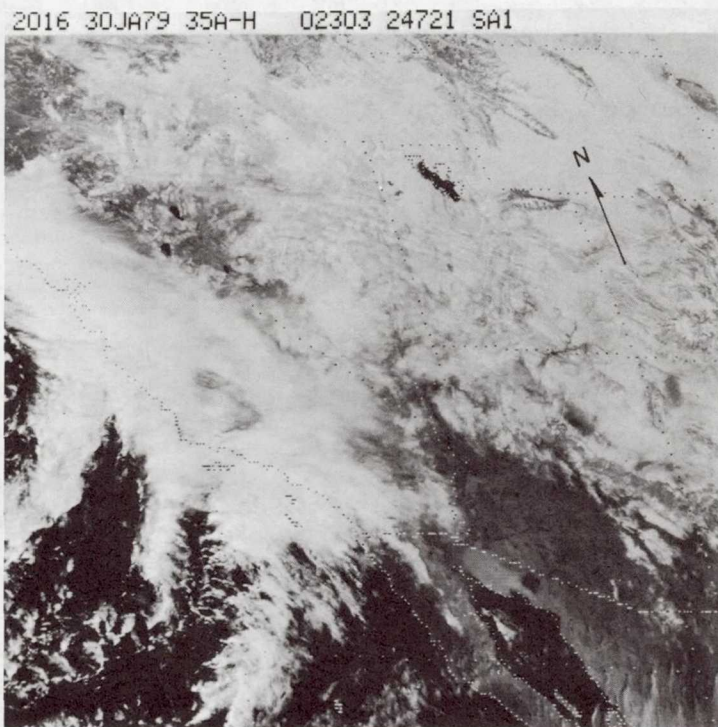


Fig. 5—SMS/GOES VISSR image taken in the visible part of the spectrum

TELEMETRY OF HYDROMETEOROLOGICAL DATA

Rapid changes in winter streamflow rates in response to rainfall and snowmelt present serious water-management problems in central Arizona. Telemetry systems are used to relay hydrometeorological data from selected sites in the Salt-Verde watershed to assist in the operation of multipurpose reservoirs and to provide flood-warning information. The systems include microwave telemetry, two satellite telemetry systems, and a meteor-burst communication system.

Microwave Telemetry System

The Salt River Project operates a conventional microwave telemetry system to monitor streamflow rates at seven key gaging stations above the reservoirs. The system can be interrogated, and the desired data can be obtained in real time. The main disadvantage of this type of system is the high cost of equipment and maintenance.

Landsat Data Collection System

During 1972-76, the experimental Landsat data collection system (DCS) was successfully tested to relay hydrometeorological data from selected streamflow-gaging stations and snow-monitoring sites (Schumann, 1975). On several occasions, the system provided valuable information to managers of the Salt River Project for use in making reservoir-management decisions during periods of large and rapidly changing runoff.

The Landsat DCS uses battery-powered data collection platforms (DCPs) to relay hydrometeorological data from remote sites via the Landsat satellites to one or more of the ground-receiving sites in California, Maryland, and Alaska (Fig. 6). The Landsat

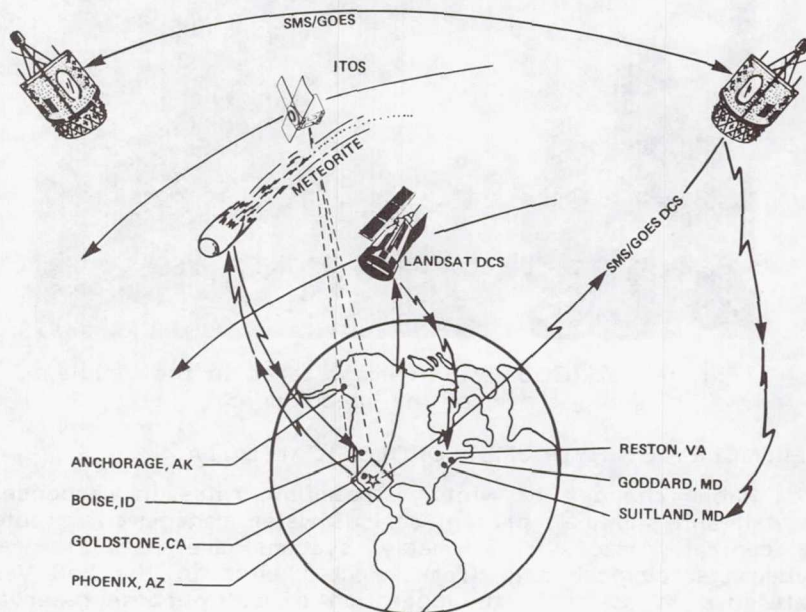


Fig. 6—Satellite telemetry systems

DCPs transmit as many as 64 bits of data every 90 or 180 seconds and relay data from anywhere in North America during at least two orbits per day—one at about 9:30 in the morning and one at about 9:30 in the evening. When the satellite is in mutual view of a transmitting DCP and one of the ground-receiving sites, the satellite relays the transmission in real time to the ground-receiving site (National Aeronautics and Space Administration, 1976).

The Landsat DCPs proved to be reliable under a wide range of environmental conditions and were simple to operate. The main disadvantages of using the Landsat DCS to relay hydro-meteorological data are the small amount of information relayed per transmission (64 bits) and the small number of transmissions received each day.

SMS/GOES Data Collection System

The operational SMS/GOES DCS telemeters large volumes of hydrometeorological data from remote sites at low cost. The SMS/GOES DCPs are operated in a self-timed mode—units transmit every 3 hours—and are microprocessor controlled. Since 1977, data from four streamflow-gaging stations and one snow-monitoring site in central Arizona have been collected at 15-minute intervals and stored in the DCP memory unit (832-bit capacity) for relay every 3 hours to the western satellite. When powered by batteries that are recharged by solar panels, the DCPs can operate unattended for long periods of time (LaBarge Incorporated, 1977).

Data transmitted by the DCPs are relayed in real time by the SMS/GOES satellites to the NOAA ground-receiving site at Wallops Island, Virginia, and are sent to the World Weather Building in Suitland, Maryland (Fig. 6). The data are then relayed to the National Center of the U.S. Geological Survey in Reston, Virginia, where the data are routinely processed into engineering units and sent to Arizona on a weekly basis via a high-speed computer terminal. Unprocessed SMS/GOES DCS data also are available from the NOAA computer center in Suitland, Maryland, in near-real time—less than 1 minute after transmission to the satellite—through the use of low-speed computer terminals. The value of near-real time satellite telemetry was dramatically demonstrated during the storms of March 1978, December 1978, and January 1979 in central Arizona. Streamflow data relayed by the system were used by personnel of the Salt River Project to monitor runoff into the Salt River and to make water-management decisions.

Snotel System

The Snotel system implemented by the Soil Conservation Service (SCS) uses a meteor-burst telemetry technique to relay

hydrometeorological data from snow-monitoring sites in the Salt-Verde watershed (Fig. 6). (See Barton and Burke, 1977.) Snow-water equivalents and other data relayed from the sites and snowcovered area measurements from satellite snowcover observations may permit improved estimates of the volume of water stored in the snowpack.

SNOWCOVER DEPLETION AND RUNOFF

The rate at which snowcover is depleted from the watershed can be considered as an index of the runoff generated by snow-melt. In the Salt-Verde watershed snow above an altitude of about 2,100 m (7,000 ft) does not melt until March, April, or May. A thin snowcover below an altitude of about 2,100 m (7,000 ft) is ephemeral and is subject to rapid melting induced by sharp increases in temperature or by rain on the snow (Warskow et al., 1975). Rain falling on snow often produces rapid increases in runoff and creates a large flood potential in the Salt River Valley when reservoirs are filled to near capacity (Warskow et al., 1975).

Statistical Analyses

Snowcovered area measurements and corresponding mean daily runoff values for the Salt and Verde Rivers are shown in Figures 7 and 8. A comparison of the measurements suggests that periods of reduction in snowcovered area often correspond to periods of changes in runoff rates. Because winter cloud cover often limits satellite snowcover observations to periods following major storms, most observed periods of reduction in snowcovered area correspond to periods of decreasing runoff rates. An example of increasing runoff rates during a period of reduction in snowcovered area occurred in late February 1978 (Figs. 7 and 8).

A linear regression analysis was used to determine the relation between snowcovered area and the corresponding runoff rates for 28 events on the Salt River and 22 events on the Verde River during 1974-78. The percentage of snowcovered area was considered as the independent variable, and the corresponding mean daily runoff was considered as the dependent variable. The simple linear regression equation developed for each event is

$$R = bS + a, \quad (1)$$

where R is the mean daily runoff in cubic feet per second, b is the regression coefficient or the slope of the regression line, S is the snowcovered area in percent, and a is the intercept along the ordinate (Ezekiel and Fox, 1959).

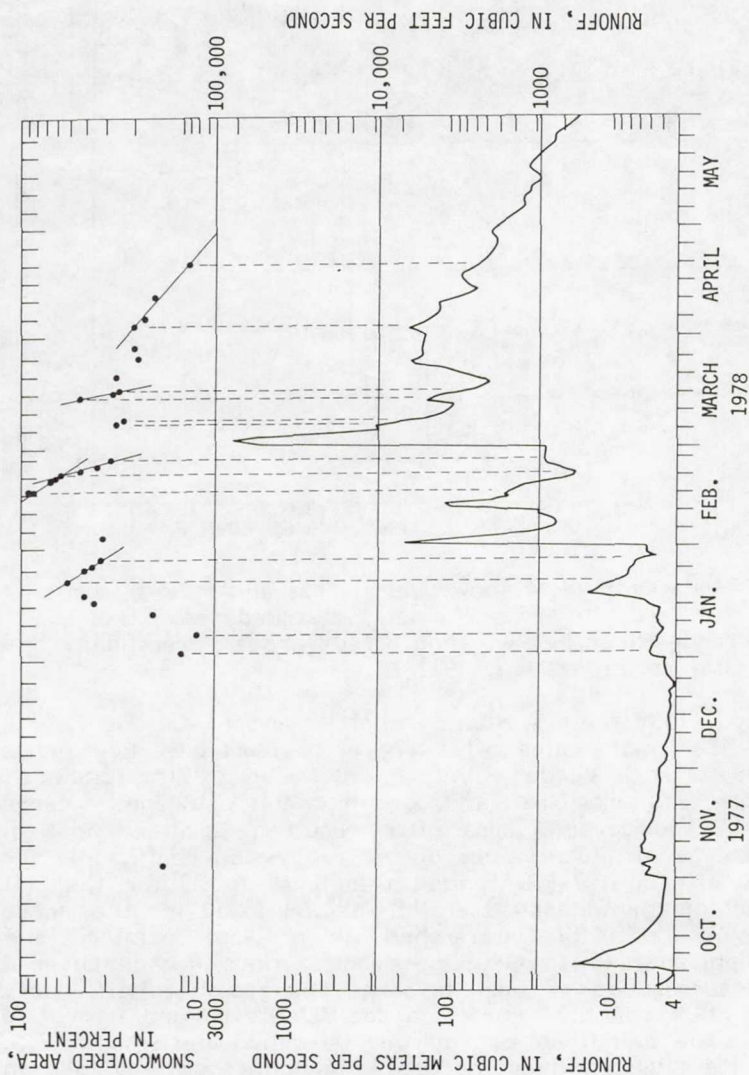


Fig. 7—Percentage of snowcovered area and runoff from the Salt River part of the watershed above the Salt River near Roosevelt gaging station, 1977-78

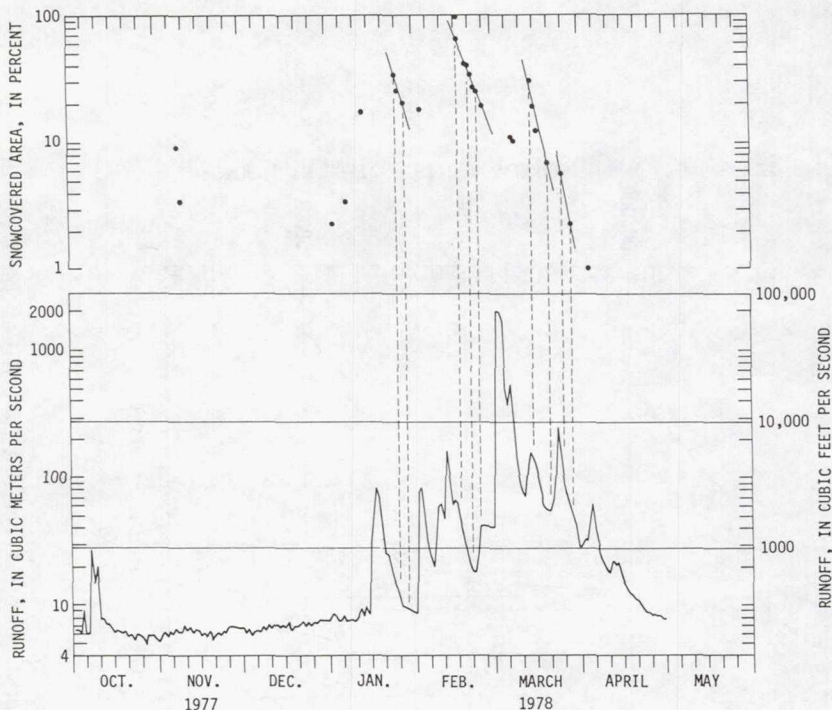


Fig. 8—Percentage of snowcovered area and runoff from the Verde River part of the watershed above the Verde River below Tangle Creek above Horseshoe Dam gaging station, 1977-78

Early in the winter runoff season—October 1 to February 15—runoff rates often are at or near base-flow levels in the Salt and Verde Rivers, and most of the snowmelt replenishes soil moisture and ground-water storage. Large changes in snowcovered area often result in small changes in runoff rates. Absolute values of the regression coefficients for winter runoff for 1974-78 ranged from 0.48 to 36 for the Salt River part of the watershed and from 0.66 to 12 for the Verde River part of the watershed. In late winter and spring—February 15 to May 15—small changes in snowcovered area can correspond to small or large changes in runoff rates. Absolute values of the regression coefficients ranged from 0.79 to 416 for the Salt River part of the watershed and from 0.88 to 233 for the Verde River part of the watershed. Values in excess of 200 were observed only in late spring—April through May.

Coefficients of determination (Ezekiel and Fox, 1959) ranged from 0.69 to 0.99+ and averaged 0.91 for the Salt River data; the coefficients ranged from 0.62 to 0.99+ and averaged 0.90 for

the Verde River data. Confidence levels ranged from 60+ to 99+ percent for both sets of data, and most were more than 85 percent. Although only a small number of measurements—3 to 7—were available for each event, the data suggest a strong relation between changes in snowcovered area and short-term changes in mean daily runoff for the Salt-Verde watershed.

Snowcovered area measurements often fall along a straight line when the logarithms of snowcovered area are plotted against time in days (Figs. 7 and 8). The same relation was observed in the Salt and Verde parts of the watershed during the 1974-75, 1975-76, and 1976-77 winter runoff seasons for which frequent sequential satellite snowcover observations were available from NESS. The relation can be expressed by the linear equation

$$\log S = bt + a, \quad (2)$$

where S is snowcovered area in percent, t is time in days after the initial snowcover measurement, and b and a are regression constants. As few as two consecutive snowcover measurements can be used to determine a first approximation of the rate of depletion of snowcovered area and to make short-term predictions of the percentage of snowcovered area (S') a few days in the future.

Short-Term Runoff Predictions

Equation 1 may be used with predicted values of snowcovered area from equation 2 to predict mean daily runoff (R'). The volume of short-term runoff can be calculated by summation of the estimates of mean daily runoff using the equation

$$V = (R'_1 + R'_2 + R'_3 + \dots + R'_n) (1.98), \quad (3)$$

where V is the volume of runoff in acre-feet, R' is the predicted mean daily runoff in cubic feet per second, and 1.98 is a constant. The short-term runoff predictions will be reasonably accurate if additional precipitation or large changes in air temperature do not occur. If a subsequent observation of snowcovered area differs significantly from the projected value, a new relation must be developed before additional runoff predictions can be made.

Seasonal Runoff Predictions

In the Salt River Project area seasonal runoff predictions are estimated to produce average annual benefits of more than \$11 million to users of runoff for the irrigation of cropland (Elliott, 1977). Seasonal runoff predictions require careful consideration of many hydrologic parameters, such as antecedent precipitation and runoff amounts, soil moisture and ground-water

storage conditions, and the volume and distribution of water stored in the snowpack. The probability of postprediction precipitation and energy exchange, which may affect snowmelt and evapotranspiration rates, also should be considered.

Operational runoff predictions are made by personnel of the SCS and Salt River Project using conventional index forecast models (Warskow et al., 1975). The models provide reasonably accurate predictions for years of low to average runoff volumes; however, the models rely strongly on averages and have greatly underestimated the large runoff volumes in recent years.

A concern for the apparent large changes in basin storage early in the winter runoff season led to the testing of the hydro-meteorological model (HM) developed by the U.S. Geological Survey in an attempt to improve runoff predictions in the Salt-Verde watershed. The model implicitly incorporates snow, soil moisture, and ground-water storage as part of basin storage (Tangborn, 1977). Seasonal runoff predictions for the March-May runoff periods for 1960-75 were developed using monthly precipitation and runoff values. A comparison of the HM predictions with the SCS model predictions indicates a reduction in the overall standard error of estimate of 42 percent for the Salt River, 46 percent for the Verde River, and 29 percent for Tonto Creek.

Further modification of the HM was necessary to develop short-term runoff predictions. The HM was modified to use daily precipitation and runoff values and to make runoff predictions of less than a month duration. The modifications resulted in an even greater improvement in the accuracy of seasonal runoff predictions (Fig. 9). The modified HM was installed on the Salt River Project computer early in 1978 for operational testing.

In spring 1978 and spring 1979 the Salt River Project used the HM to make seasonal and short-term runoff predictions. Additional modification of the HM to include air-temperature data resulted in a 22-percent improvement in the short-term runoff predictions for the Black River near Fort Apache in the upper part of the Salt River watershed (Tangborn, written commun., 1978). Additional research is needed to allow the effective use of snowcovered area measurements in future seasonal runoff predictions. Repetitive satellite snowcover observations concurrent with hydrometeorological data relayed in near-real time from snow-monitoring and streamflow-gaging sites should facilitate the research.

CONCLUSIONS

The availability of frequent satellite snowcover observations has greatly reduced the necessity for routine aerial reconnaissance flights over the Salt-Verde watershed. Significant savings

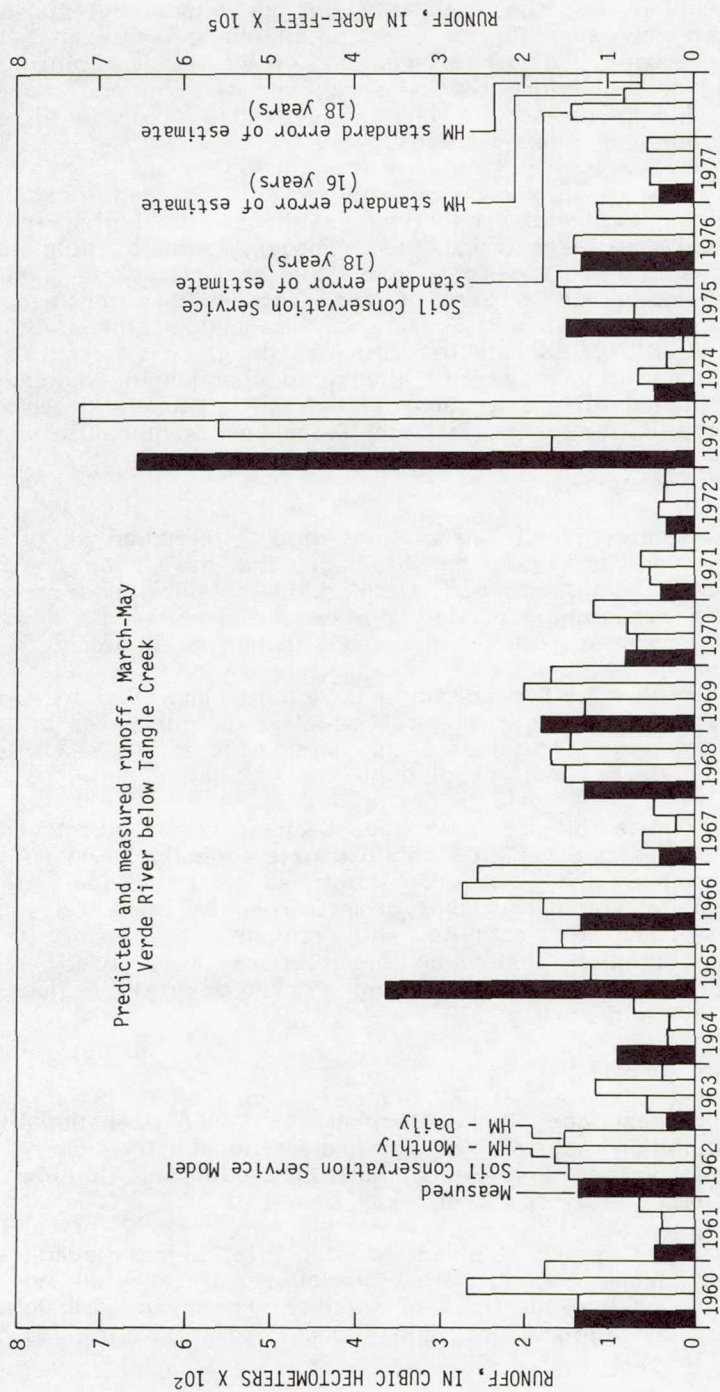


Fig. 9—Seasonal runoff predictions, Verde River below Tangle Creek

have resulted, and the time that flight crews must be exposed to hazardous low-level flights over mountainous terrain has been greatly reduced. Aerial observations, however, will continue to provide valuable information on snowcover distributions and snow depths during periods of cloud cover that preclude effective satellite snowcover observations.

Satellite imagery provides the synoptic coverage needed for mapping large snowcovered areas. Although the high-resolution experimental multispectral Landsat imagery permits rapid snowcover mapping at low cost, only one observation is available every 9 days for a part of the Salt-Verde watershed. In contrast, low-resolution operational imagery acquired by the ITOS and SMS/GOES satellites provides the daily synoptic observations necessary to monitor the rapid changes in snowcovered area in the entire Salt-Verde watershed. However, geometric distortions in meteorological satellite imagery require the use of specialized optical equipment or digital-image processing for snowcover mapping.

Short-term runoff predictions and information on basin-storage conditions can be made on the basis of snowcover depletion rates determined from daily satellite observations. Additional research is needed to allow the effective use of snowcovered area measurements in seasonal runoff predictions.

Seasonal runoff predictions have been improved by use of the modified hydrometeorological model in recent years of large runoff volumes. The model also was modified successfully to make short-term runoff predictions.

Hydrometeorological data have been successfully relayed by the Landsat and SMS/GOES satellite data collection systems from remote sites on the Salt-Verde watershed under a wide range of environmental conditions. Hydrometeorological data relayed in near-real time by satellite and conventional telemetry and frequent satellite snowcover observations were used as an integral part of an early warning system during the floods of spring 1978 and spring 1979.

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